# Early-Type Contact Systems in the LMC MACHO Database

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ABSTRACT

Two sub-samples of blue, luminous contact systems from among 86 systems discovered in LMC by the MACHO project and classified as EB3 have been analyzed: a sub-sample of 29 extremely-blue systems (XB) with the observed colors $V - R_C < -0.1$ and a sub-sample of 36 moderately-blue (MB) systems with $-0.1 < V - R_C < 0$. To be so blue, the XB systems must be intrinsically very hot and almost unreddened so that lack of information on reddening is unimportant for them; their properties offer us a first-time insight into the absolute-magnitude calibration for massive contact binaries. It has been found that the LMC systems are apparently not limited by the blue, short-period envelope in the color-period diagram which had been established on the basis of systems observed in the solar neighborhood, in galactic open clusters and in the sample of Old Disk systems in the direction of the Galactic Bulge. The period–magnitude correlation for the XB systems has a similar slope to those established in the absolute-magnitude, $B - V$ and $V - I_C$ based, calibrations for W UMa-type systems.

## 1 Introduction

Calibrations of the form $a_P \log P + a_C \mathrm{color} + a_0 = M_V$ are relatively successful in predicting absolute magnitudes of contact binaries of the W UMa-type. They have been established on the basis of systems in open clusters (Rucinski 1994a) and then improved for the solar neighborhood using the Hipparcos data (Rucinski and Duerbeck 1997); with metallicity corrections, they can be used for globular clusters as well (Rucinski 1994b, 1995). They have been invaluable in handling the Galactic Disk and open cluster data for contact binaries (Rucinski 1998a). It would be very useful to establish a similar calibration for contact binaries of early spectral types because such binaries are now being detected in large numbers in nearby galaxies (Kałużny *et al.* 1998, Stanek *et al.* 1998, Stanek *et al.* 1999) and may eventually provide independent distance estimates.

Contact binaries of spectral earlier than middle-A and periods longer than about 1.5 day are very rare in the Galaxy. They practically do not exist in the OGLE Galactic-Bulge database which probes mostly the Old Disk population (Rucinski 1997a, 1998a); the period distribution of contact binaries abruptly ends at about 1.3–1.5 days (Rucinski 1998b). This cut-off can be explained by non-existence of Old Disk main-sequence stars with masses much larger than the solar mass. Intrinsically bright, massive contact binaries, such as the systems discussed by Popper (1982) – with periods of a few days and masses of several solar masses – do exist within our Galaxy, but their frequency of occurrence is apparently exceedingly low and currently unknown. It is important that they share the same property of identical effective temperatures of components – in spite of strongly differing masses – with the solar-type contact binaries of the W UMa-type. This property basically defines the W UMa-type stars.

The currently ongoing microlensing projects lead to discoveries of large numbers eclipsing binaries in Magellanic Clouds. This paper presents a pilot study based on the data for contact binaries in the Large Magellanic Cloud (LMC) which have been collected by the MACHO project (Alcock *et al.* 1997). In the next sections, we describe various properties of the early-type contact systems in the MACHO sample. The electronically-available database (American Astronomical Society CD-ROM Series, Vol. 8, 1997) contains the summary, time-independent data and plots of the light curves, and is quite typical for microlensing projects. It can be treated similarly as the one obtained by the OGLE project for the direction toward the Galactic Bulge (Rucinski 1997a). In this spirit, only the mean quantities such as the period, the maximum and the in-eclipse $V$-magnitudes as well as the maximum-light $V-R_C$ color index in the Kron–Cousins system have been used. Availability of this particular index is somewhat unfortunate because the previous absolute-magnitude calibrations for W UMa-type systems were based on the $B-V$ and $V-I_C$ indices so that the existing calibrations can be used only for general guidance, but not for detailed comparisons.

# 2 The Sample

The definition of W UMa-type contact systems (normally abbreviated as EW) does not include binaries with periods longer than one day. In the MACHO database of the eclipsing binaries discovered in LMC (Alcock *et al.* 1997) such systems are called EB, with a subset of them, with eclipses of similar depth indicating similar surface brightness of components, designated as EB3. The EB3 systems have been used in this paper, keeping in mind subjectivity of this definition. Electronically available plots of the light curves confirm, that the light-curve shapes are indeed very typical for contact binaries, as shown for the example in Fig. 7 in Alcock *et al.* (1997). There are 86 systems of this type in the MACHO database.

In addition to the values of the orbital periods, the photometric data are important for discussions of this paper. The precision of the MACHO data is moderate: The mean standard error of $V$ magnitudes is about 0.07 while the mean standard error for the color index $V-R_C$ is about 0.03. The accuracy (which reflects the role of systematic errors) is limited for the MACHO sample by the use of the non-standard bandpasses which are not defined – as usually – by glass filters, but by a dichroic filter separating the bands, and by transmission characteristics of the CCD's and of the atmosphere.

Fig. 1. Histograms of the amplitudes (left panel) and eclipse-depth differences (right panel) in $V$ magnitudes for the whole sample of 86 EB3 systems (continuous line) and for the sub-sample of blue systems with the observed color index $V-R_C<0$ (shaded area).

The histograms of the $V$-magnitude amplitudes and minimum differences shown in Fig. 1 are quite typical for contact systems. The largest amplitudes observed are slightly over 0.8 mag and the minimum differences are typically in the range of 0 to 0.02 mag, as for genuine W UMa-type systems (see Fig. 2 in Rucinski 1997b; the magnitude difference is approximately twice the Fourier coefficient $a_1$ shown there). The limit for inclusion in the database was the variability amplitude larger than 0.2 mag. Contact binaries with still smaller variability amplitudes are expected to be actually the most frequent for randomly distributed orbital inclinations (Rucinski 1997b).

## 3 The Color–Magnitude Diagram (CMD)

The CMD for the contact systems considered here shows a concentration of the systems at the left, blue edge of the diagram and a scattered population

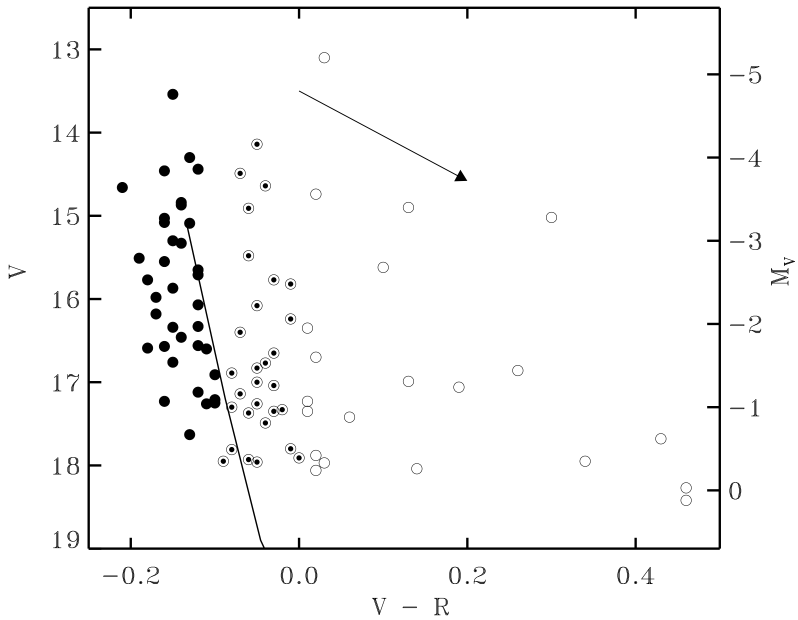


Fig. 2. The color–magnitude diagram for the MACHO sample of contact binaries. The limits at $V - R_C = -0.1$ and 0 define three ranges that we consider in the paper. The binaries bluer than $V - R_C = -0.1$ (XB group) are marked by filled circles while those redder than $V - R_C = 0$ are marked by open circles; the semi-filled circles are for $-0.1 < V - R_C < 0$ (MB group). The bluest objects are those that are intrinsically hottest and least reddened. The curve at the left edge gives the Zero Age Main Sequence following Schmidt-Kaler (1982); it is shown without any correction for interstellar reddening. For simplicity, the distance modulus $m - M = 18.3$ was assumed, but this value is not used in the paper for any purpose. The arrow gives the reddening vector $A_V = 5.4 E_{V-R_C}$.

of systems in the red part of the diagram (Fig. 2). Since the available data are in two photometric bands only, we have no information about reddening of individual objects. Reddening in LMC is patchy and varies within $0 < E_{B-V} < 0.4$, but with excursions up to 0.8 (Harris *et al.* 1997). In this situation, it has been decided to limit our considerations to the systems at the left edge of the CMD which are intrinsically the bluest and least-reddened. The systems in the red part of the diagram in their majority have long orbital periods (see the next Section and Fig. 3) and we do not have a good explanation for them. In what follows, we will consider three groups of the contact binaries defined by the observational $V-R_C$ color ranges: the extremely blue (XB) systems with $V-R_C<-0.1$, the moderately blue (MB) systems with $0.1<V-R_C<0$ and the red systems with $V-R_C>0$; the latter are not discussed here at all.

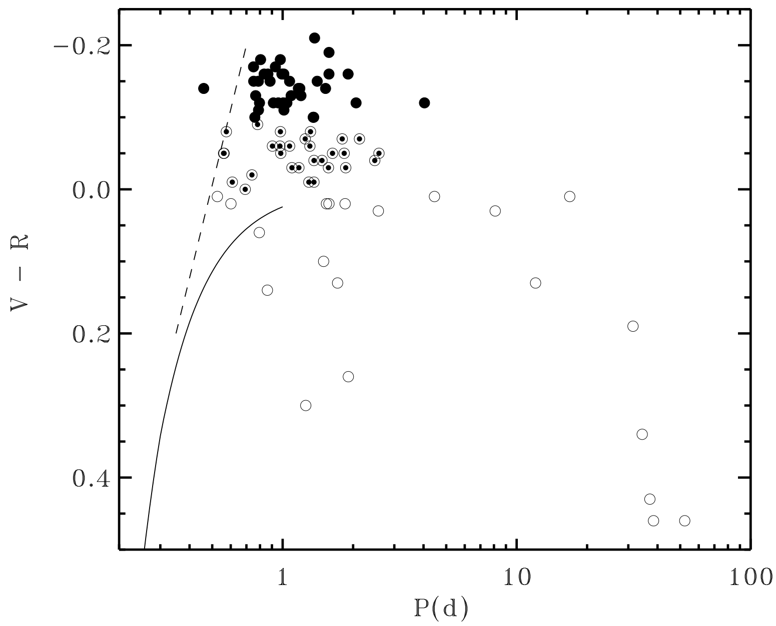


Fig. 3. The period-color diagram with symbols as in the previous figure. The curved line is the Short-Period Blue Envelope (SPBE) previously found to limit location of least-evolved contact binaries in the Galaxy. The broken line gives a suggested location of the SPBE on the assumption that the Galactic sample did not include sufficiently un-evolved objects.

# 4 The Period–Color Diagram (PCD)

The period-color diagram is shown in Fig. 3, with the same color-range symbols as in Fig. 2. The curved line at the left edge gives the Short-Period Blue-Envelope (SPBE) for the Galactic-Disk sample, $(V-I_C)=0.053P^{-2.1}$ (Rucinski 1997a), after application of the color-color transformation to $V-R_C$ using Table 3 in Taylor (1986). It is obvious that the LMC systems are seen beyond the blue limit of the SPBE which was previously found to obey for all contact binaries in the galactic field and in all open clusters. The low metallicity of LMC ($[Fe/H] = -0.5$) cannot produce the shift because the intrinsic color indices for main-sequence OB stars have a negligible dependence on metallicity (Oestreicher *et al.* 1995). We strongly suspect that by considering the bluest contact systems, we are also looking at objects of a young stellar population which simply does not exist in the solar neighborhood or in old open galactic clusters. It is possible, that the curvature of the SPBE that was found before was entirely due to the lack of young objects in the previously-used samples; possibly, the real location of the SPBE is closer to what has been marked by a broken line in Fig. 3.

A closer inspection of the PCD in Fig. 3 shows that the blue contact systems in LMC have orbital periods up to 2–3 days, whereas in the disk sample of OGLE the period distribution was found to a sharp cut-off at about 1.3–1.5 days (Rucinski 1998b). There are too few systems in the MACHO sample to analyze statistically the numbers of systems with periods above 1.3 days, however.

## 5 The Period–Luminosity Relation

The contact systems in LMC are practically in the same distance from us so that the initial goal of this study was an attempt to establish an absolute-magnitude calibration of the type $a_P \log P + a_{VR}(V - R_C) + a_0 = M_V$. However, this goal is impossible to achieve at this time for the following reasons: (1) Lack of reddening information prevents determination of reddening and absorption corrections for individual systems; (2) $V - R_C$ color index, as other ones utilizing optical spectral bands, loses sensitivity to the effective temperature for very hot stars and hence must be determined with high accuracy; (3) The observed color indices have modest precision of about 0.03 mag and an uncharacterized accuracy due to the use of the non-standard band-passes. At present, one can only address the matter of period dependence in the observed values of $V_{\max}$. Such a limited goal is still a valuable check on the assumptions because a period dependence is expected only for genuinely contact systems and it is by no means obvious that the systems classified as EB3 are indeed contact ones. For detached binaries, no relation between period and component brightness is expected.

The period – observed-magnitude diagram for the sample is shown in Fig. 4. As one can see, the systems of both groups, the extra-blue (XB) and

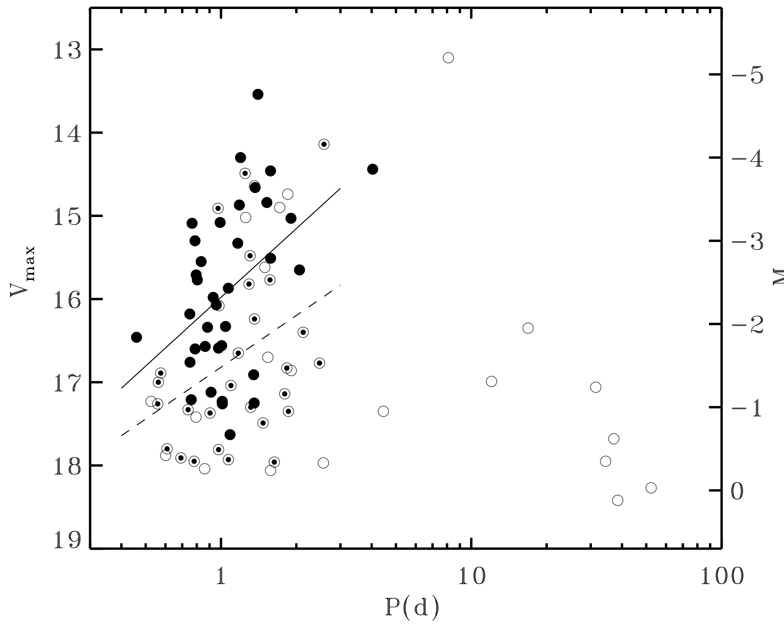


Fig. 4. The relation between the orbital period and the $V$-magnitude at maximum light for the systems of the MACHO sample. The same symbols as in the previous figures are used to distinguish the three color index ranges. The lines give linear fits to the XB (solid line) and MB (broken line) sub-samples.

the moderately-blue (MB) systems, show some period dependence, but the scatter of points is large, probably mostly because of the unaccounted effects of the interstellar reddening and extinction. We note also that there are more MB systems in the vicinity of the faint-limit of the sample at $V_{\rm max} \simeq 18$ than XB systems. Least-squares fits of the form $V_{\rm max} = a_0 + a_1 \log P$ have been performed for both samples; we note that the orbital periods $P$ are known practically without errors. Because the scatter of the data is large, uncertainties of the coefficients crucially depend on the data sampling. To characterize this effect, the errors of the coefficients $a_i$ have been determined using the bootstrap re-sampling technique. The results are listed in Table 1 in terms of the median values and the 68 percent (for Gaussian distributions, $\pm$1-sigma) and 95 percent ($\pm$2-sigma) confidence levels.

Histograms of the individual values of the zero-point and slope coefficients from the bootstrap experiment are shown in Fig. 5. Note that the mean color indices for the XB and MB groups are $\overline{V - R_C} = -0.142$ and $-0.047$, while the difference of the zero points is: $a_0(\rm MB) - a_0(\rm XM) = 0.84$.

Table 1

Bootstrap results and significance ranges for coefficients of the fits: $V_{max} = a_0 + a_1 \log P$

| | XB | | MB | |
|---|---|---|---|---|
| | $a_0$ | $a_1$ | $a_0$ | $a_1$ |
| $-95\%$ ($-2\sigma$) | 15.69 | $-4.47$ | 16.45 | $-4.09$ |
| $-68\%$ ($-1\sigma$) | 15.83 | $-3.43$ | 16.65 | $-3.07$ |
| median | 15.98 | $-2.74$ | 16.82 | $-2.07$ |
| $+68\%$ ($+1\sigma$) | 16.12 | $-2.17$ | 17.00 | $-1.24$ |
| $+95\%$ ($+2\sigma$) | 16.28 | $-1.36$ | 17.16 | $-0.37$ |

This would imply a very strong dependence on the color index with a steep slope of about 8.8, but part of this is almost certainly contributed by the relatively larger reddening for the MB group. Much more interesting are the period-dependence slope coefficients $a_1$. The determination of $a_1$ for the XB group is surprisingly stable, given the large scatter of the data points and the fact that the value of $a_1$ is driven mostly by the outlying points, $a_1(\mathrm{XB}) = -2.74^{+0.58}_{-0.68}$; the range given here is equivalent to the *rms* error of 1-sigma. The determination for the MB group is poorer, $a_1(\mathrm{MB}) = -2.07^{+0.83}_{-1.00}$, probably because the presence of the faint cut-off in the data and certainly stronger influence of the scatter in the reddening values for this group. When compared with the calibrations for the W UMa-type binaries using the $B-V$ and $V-I_C$ indices (*cf.* Eqs. (2) and (5a) in Rucinski and Duerbeck 1997), the slope $a_1(\mathrm{XB}) = -2.74$ is rather shallow (the previous calibrations implied the slope of about $-4.4$) which may have resulted from relatively large photometric errors of the MACHO data.

# 6 Conclusions for the Future

The main result of this pilot study is that the sample of EB3 binaries discovered and classified by the MACHO project certainly contains hot, blue, massive binaries of the contact type. Although it may have been preferable to make the selection of the systems on the basis of the Fourier coefficients – rather than to rely on the MACHO classifications – this was not necessary because the systems reveal typical properties of contact-binary stars. The contact nature of these binaries is most strongly confirmed by the existence

Fig. 5. Histograms of the coefficients $a_0$ and $a_1$ in the fits $V_{\max} = a_0 + a_1 \log P$ obtained from a bootstrap re-sampling experiment for the sub-samples of extremely-blue (XB, continuous line) and moderately-blue (MB, broken line) systems. These distributions have been used to establish the uncertainty estimates given in Table 1.

of a period–luminosity relation which is best visible in the XB sub-sample consisting of the bluest and least reddened systems. The new result is that the massive, young, blue systems in LMC are apparently not constrained by the previously-established short-period blue envelope in the period–color diagram and appear with blue-color/short-period combinations not observed in the previous surveys of the open clusters in the Galaxy and in the Galactic Disk field. These systems appear also within the orbital period interval of 1.3–1.5 to 2–3 days, a range for which the frequency of the galactic contact systems is known to be un-measurably low.

An important conclusion related to the future attempts of determining an absolute-magnitude calibration for early-type contact systems is the availability of accurate color indices. Photometry should be available in at least three bandpasses for reddening determinations, and must be accurate enough (through the use of the standard filter bands and a requirement that mean standard errors be $< 0.01$ mag) to compensate for the decreased sensitivity of optical color indices to effective temperature. For comparison and consistency checks with the results for solar-type contact binaries of the W UMa-type, it would be preferable to utilize $B-V$ and $V-I_C$ color indices. The new database for SMC coming from the OGLE-II project (Udalski *et al.* 1998) apparently fulfills most of the above desiderata.

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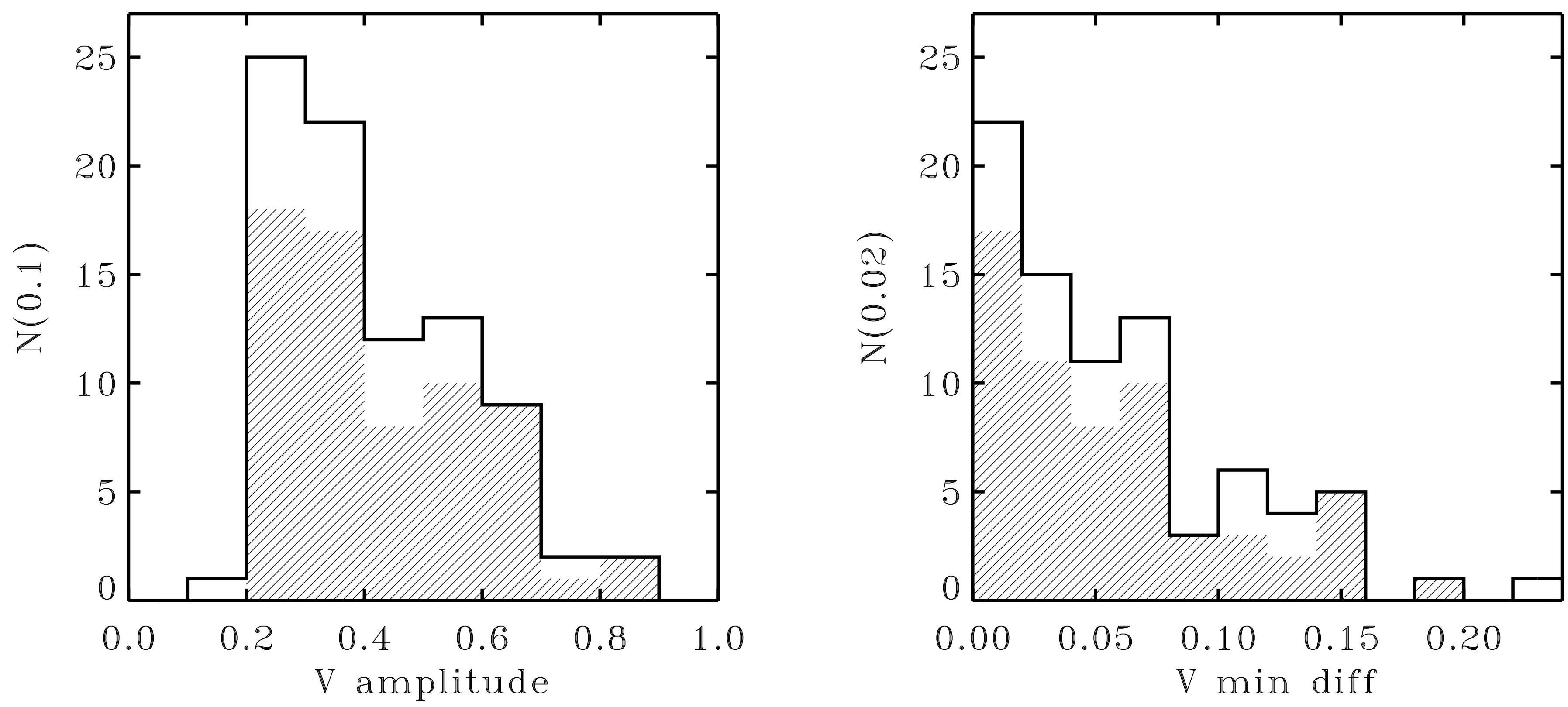
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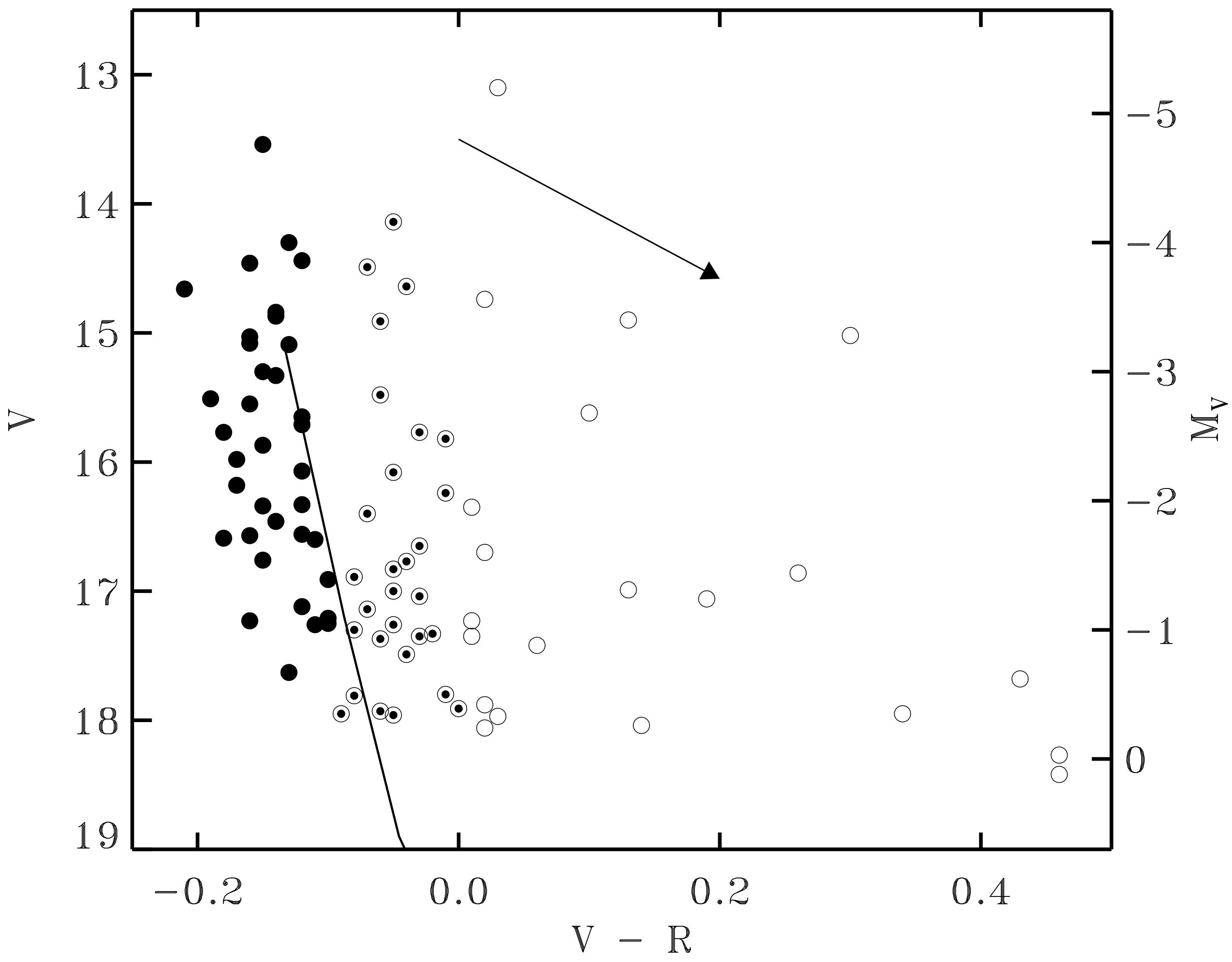
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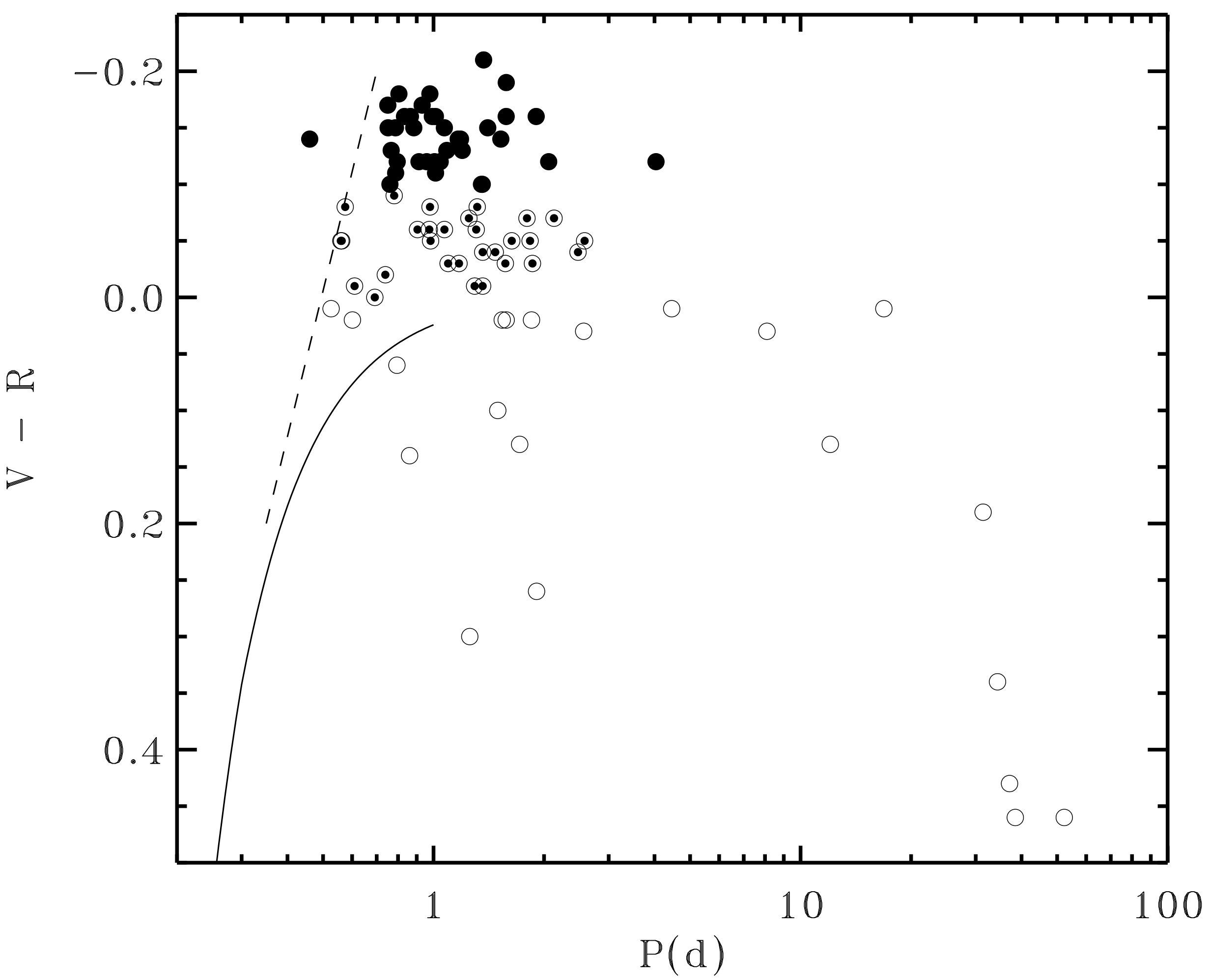

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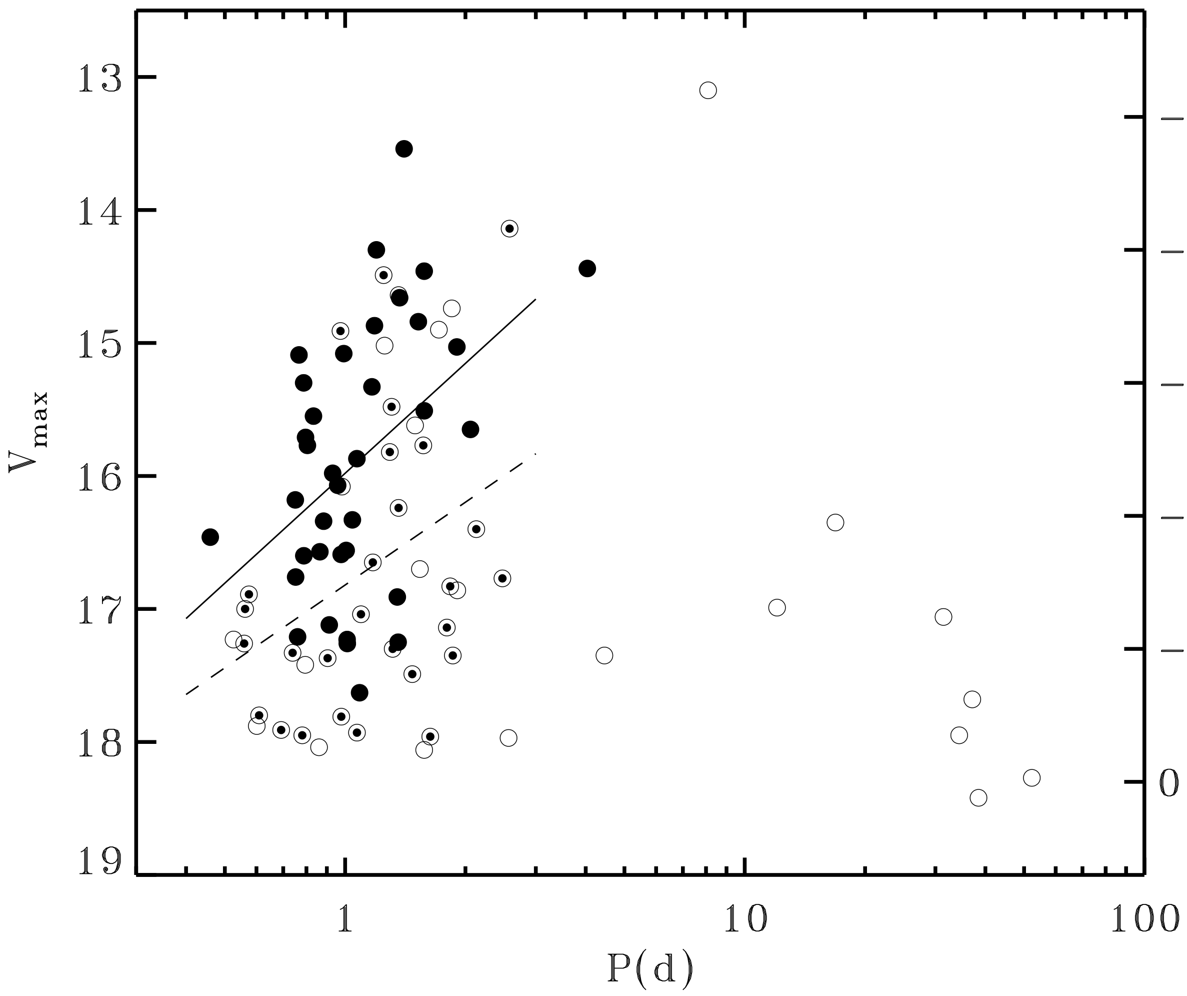
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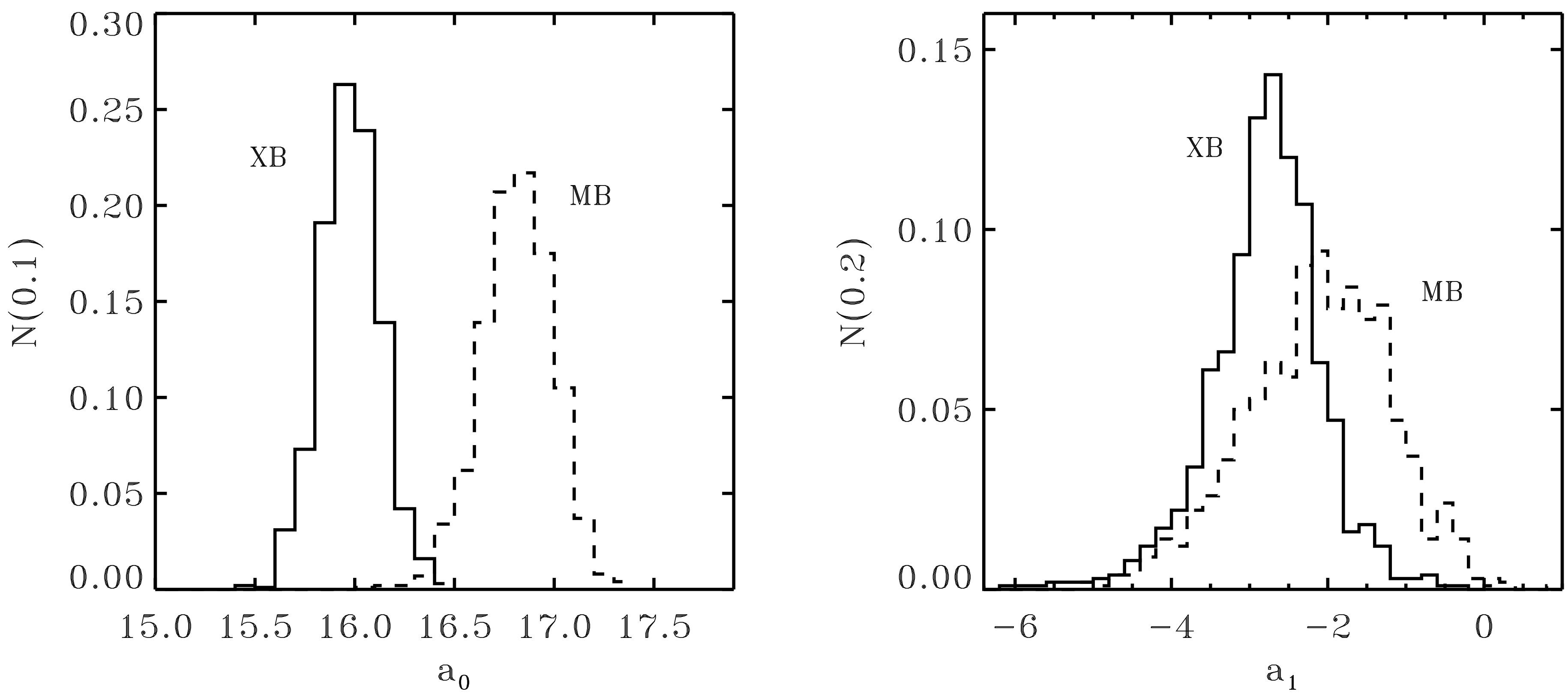

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